

Higgs Physics Beyond the Standard Model

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ABSTRACT

Higgs physics beyond the Standard Model (SM) is presented in the context of an underlying strong dynamics of electroweak symmetry breaking (EWSB) as given by composite Higgs models. Subsequently, the study of New Physics (NP) effects in a more model-independent way through the effective Lagrangian approach is briefly sketched before moving on to the investigation of NP through Higgs coupling measurements. Depending on the precision on the extracted couplings, NP scales up to the TeV range can be probed at the high-luminosity option of the LHC, if the coupling deviations arise from mixing effects or from some underlying strong dynamics.

PRESENTED AT

The Second Annual Conference
on Large Hadron Collider Physics
Columbia University, New York, U.S.A
June 2-7, 2014

1 Introduction

The announcement of the discovery of a new scalar particle by the Large Hadron Collider (LHC) experiments ATLAS and CMS [1, 2] has immediately triggered activities to determine the properties of this particle. The measurement of its couplings to other SM particles and the extraction of its spin and parity quantum numbers are steps in order to establish the scalar as *the* Higgs boson, *i.e.* the particle related to EWSB. Any deviations in these properties from the SM expectation would hint to physics beyond the SM (BSM). Although the Higgs boson looks very SM-like, there is still room for interpretations within BSM theories. In absence of any direct detection of NP particles, the Higgs sector becomes particularly interesting. The precise measurements of the Higgs properties help to reveal the underlying mechanism of EWSB and in particular may shed light on the question if the underlying dynamics is strongly or weakly interacting. An example for the latter are supersymmetric (SUSY) extensions of the SM which remain weakly interacting up to high energies. The talk, that is summarised here, focuses on non-SUSY extensions of the SM. Composite Higgs Models shall be presented as theories emerging from a strongly interacting sector, before moving on to effective theory descriptions that allow for a more model-independent investigation of the Higgs sector. The last part finally is dedicated to specific (non-SUSY) models and how they can be probed through coupling measurements.

2 Composite Higgs Boson

In composite Higgs models the Higgs boson arises as a pseudo Nambu-Goldstone boson from a strongly-coupled sector [3]. As result of the Goldstone nature of the Higgs boson, in the Strongly Interacting Light Higgs (SILH) scenario [4] there is a light narrow Higgs-like scalar, which is the bound state from some strong dynamics and which is separated by a mass gap from the other usual resonances of the strong dynamics. At low energy, the particle content is hence the same as in the SM. The Higgs couplings to the SM particles, however, are modified [4]. In composite Higgs models the problem of the generation of fermion masses is solved by the hypothesis of partial compositeness [5]. The SM fermions, which are elementary, couple linearly to heavy states of the strong sector with the same quantum numbers, implying in particular the top quark to be largely composite. The global symmetry of the strong sector is explicitly broken by these couplings, and the Higgs potential is generated from loops of SM particles with the dominant contribution coming from the top quark. As has been shown in Ref. [6] a low-mass Higgs boson of ~ 125 GeV can naturally be accommodated only if the heavy quark partners are rather light, with masses below about 1 TeV. From a phenomenological point of view, the modified Higgs couplings to the SM particles not only change the Higgs production and decay rates [7, 8], but notably lead to an increase of the cross section for double Higgs production in vector boson fusion with the energy [4, 9]. Furthermore, composite Higgs models are challenged by electroweak precision tests (EWPTs) [4, 10]. The tension with the S and T parameters [11]

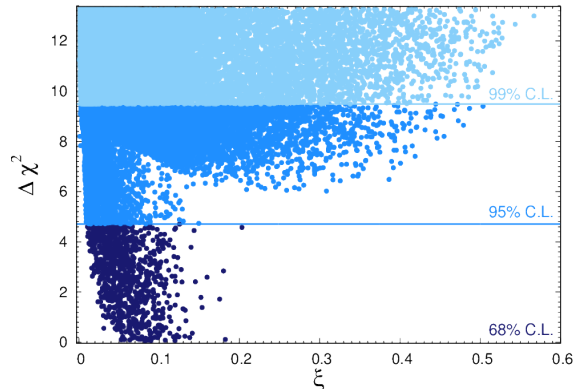


Figure 1: Parameters passing the χ^2 test of electroweak precision observables, which fulfill $|V_{tb}| > 0.92$, [13].

can be weakened through the contributions from new heavy fermions [12, 13]. This is shown in Fig. 1 for a model with composite bottom quarks, where the fermions are embedded in the **10**, the smallest possible representation of $SO(5)$ that allows for partially composite bottom quarks while being compatible with the EWPTs by implementing custodial symmetry. Performing a χ^2 test, taking into account the EWPTs and the measurement of V_{tb} [14], it displays $\Delta\chi^2 = \chi^2 - \chi^2_{\min}$ as a function of ξ for the points passing the test after a scan over the model parameters. Here $\xi = v^2/f^2$, where $v \approx 246$ GeV is the vacuum expectation value and f the typical scale of the Goldstone bosons of the strong sector.

As long as no heavy fermion partners have been detected directly, their influence on loop induced processes like Higgs production through gluon fusion becomes particularly interesting. It has been shown, that the process computed by applying the Low-Energy Theorem (LET) [15] is insensitive to the details of the couplings and masses of the strong sector [16, 17]. In double Higgs production, however, the LET is not reliable any more [18] and the cross section becomes sensitive to the properties of the strong sector [17, 19]. Also the production of a boosted Higgs boson in association with a high-transverse momentum jet is sensitive to the details of heavy fermions [20, 21] and can be exploited to measure the Higgs coupling to top pairs, as shown in Fig. 2 from Ref. [21].

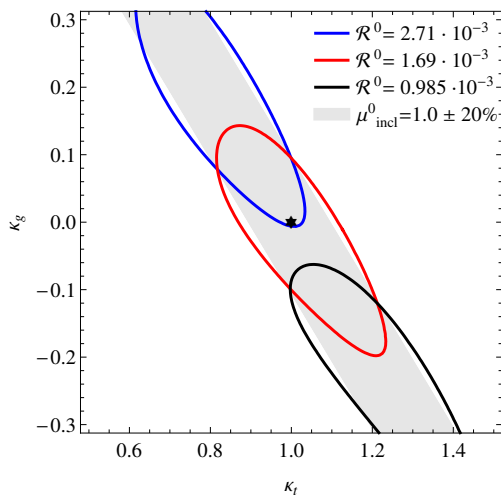


Figure 2: The 95% confidence level (C.L.) contours from a χ^2 test, in the plane of the top and effective gluon coupling modifiers κ_t and κ_g for different values of the inclusive signal strength μ_{incl}^0 and the boosted observable \mathcal{R}^0 . For details, see [21].

3 Effective Lagrangian Approach

The plethora of NP extensions calls for an effective framework that captures NP effects in a model-independent way. The scale Λ at which NP becomes effective, proposed by natural mechanisms of EWSB, is not far from the TeV scale, so that a convenient framework for a model-independent analysis of deviations from the SM is given by an effective Lagrangian approach which enlarges the SM by including higher-dimensional operators built from SM fields [22, 23]. At the dimension-6 level, there are 59 linearly independent operators, taking into account only one fermion generation and allowing also for CP-odd operators [23, 24]. There has been some discussion not only about the most appropriate basis to use but also about the minimum number of operators that should be applied to best capture the NP impact on Higgs physics. As it is impossible to review in this short text all contributions in this field a few recent results shall be highlighted in the following. The authors of Ref. [25] found that for one family there are 8 CP-even operators that, at tree-level, can only affect Higgs physics and no other SM processes. In a bottom-up approach, taking as starting point all possible new interactions among SM fields, the authors of Refs. [26, 27] derived the set of independent new

interactions at the dimension-6 level, that are presently best tested by the experiments and that give the best way to constrain NP. They found 18 of these BSM primary effects, not taking into account four-fermion deviations, minimal flavour violation suppressed deviations and those arising from CP violation. There are 8 Higgs primaries, 7 EWPT primaries and 3 primaries affecting triple gauge boson couplings (TGC). All other NP effects are not independent and are correlated with the BSM primaries, see also [24, 28]. In particular it is found, that large NP effects can still be revealed in the Higgs decay $H \rightarrow Z\gamma$ [29], while the deviations from the SM in the differential distributions of Higgs decays into a vector boson and a fermion pair are already constrained from TGC measurements [27].

4 Higgs Coupling Measurements as a Probe for New Physics

The effective field theory approach has the advantage to allow for the study of a large class of models in a rather model-independent way. However, it cannot account for effects from light particles in the loops or for Higgs decays into light non-SM particles. In order to give a complete picture of BSM effects in the Higgs sector the effective approach therefore has to be complemented by studies in specific models, that ideally capture these features. The subject of this section is the information that can be obtained from the measurement of the Higgs couplings, in particular also on the scale of NP, both in the effective Lagrangian approach and in specific models. For a review, see [30]. Deviations in the Higgs couplings due to NP can occur from two effects. The couplings can be modified due to the mixing of the standard Higgs field with other scalar fields. This is *e.g.* the case in portal models, where the SM Higgs field is coupled with a hidden sector, or in extensions of the simplest Higgs sector by a second Higgs doublet. The second class of mixing effects arises from vertex corrections of Higgs couplings to SM particles due to virtual contributions of new gauge bosons, scalars or fermions. Such loop effects can occur in various models like *e.g.* supersymmetry, extra dimensions, see-saw models, strong dynamics or extended gauge groups.

Characterising NP effects by higher dimensional operators [22, 23], the deviations of the Higgs couplings g from the corresponding SM couplings g_{SM} are of the order of

$$g = g_{\text{SM}}[1 + \Delta], \quad \text{with } \Delta = \mathcal{O}(v^2/\Lambda^2), \quad (1)$$

where $\Lambda \gg v$ is the characteristic BSM scale.* Depending on the precision Δ with which the couplings are measured this allows then to probe mass scales of the order of $\Lambda = \frac{v}{\sqrt{\Delta}}$. For coupling modifications that are generated by loop effects, there is an additional loop suppression factor $1/(16\pi^2)$ that adds to potentially small couplings between the SM and the new particles, so that only scales up to $\Lambda < v/(4\pi\sqrt{\Delta})$ can be probed. Loop effects are therefore less promising for the indirect exploration of NP scales than mixing effects.

Table 1 summarises the present precision on the couplings from measurements at the LHC [32, 33] and the accuracy that can be achieved at the high-luminosity (HL) run of the LHC, at a future e^+e^- linear collider (LC) [33, 34] and from the combination of the HL-LHC and HL-LC results. The extracted limits on the effective scales Λ_* from the contributions of the dimension-6 operators taking into account these coupling precisions are shown in Fig. 3. They have been obtained with SFitter [32] after defining the effective scales Λ_* , that are obtained by factoring out from the operators typical coefficients like couplings and loop factors. Furthermore, in the loop-induced couplings to the gluons and photons only the contributions from the contact terms are kept. The effects of the loop terms are already disentangled at the level of the input values Δ .

In the context of composite Higgs models, based on the estimates of potential deviations from SM Higgs couplings, bounds have been derived on the compositeness parameter ξ . These in turn translate into bounds on the compositeness scale f and are summarised in Table 2. They are given for two different models, the MCHM4 and MCHM5. Built in a five dimensional warped space, they provide a resummation of the full series in ξ , while the SILH Lagrangian should be seen as an expansion in ξ and can describe composite Higgs models only in the vicinity of the SM limit. The bulk gauge symmetry $SO(5) \times U(1)_X \times SU(3)$ is broken down to the SM gauge group on the ultraviolet boundary and to $SO(4) \times U(1)_X \times SU(3)$ on the infrared. In the MCHM4 [35] the SM fermions transform as spinorial representations, in the MCHM5 [36] as fundamental

*This does not hold in case the underlying model violates the decoupling theorem [31].

coupling	LHC	HL-LHC	LC	HL-LC	HL-LHC + HL-LC
hWW	0.09	0.08	0.011	0.006	0.005
hZZ	0.11	0.08	0.008	0.005	0.004
htt	0.15	0.12	0.040	0.017	0.015
hbb	0.20	0.16	0.023	0.012	0.011
$h\tau\tau$	0.11	0.09	0.033	0.017	0.015
$h\gamma\gamma$	0.20	0.15	0.083	0.035	0.024
hgg	0.30	0.08	0.054	0.028	0.024
h_{invis}	—	—	0.008	0.004	0.004

Table 1: Expected accuracy at the 68% C.L. with which fundamental and derived Higgs couplings can be measured; the deviations are defined as $g = g_{\text{SM}}[1 \pm \Delta]$ compared to the Standard Model at the LHC/HL-LHC (luminosities 300 and 3000 fb^{-1}), LC/HL-LC (energies 250+500 GeV / 250+500 GeV+1 TeV and luminosities 250+500 fb^{-1} / 1150+1600+2500 fb^{-1}), and in combined analyses of HL-LHC and HL-LC. For invisible Higgs decays the upper limit on the underlying couplings is given. Taken from [30].

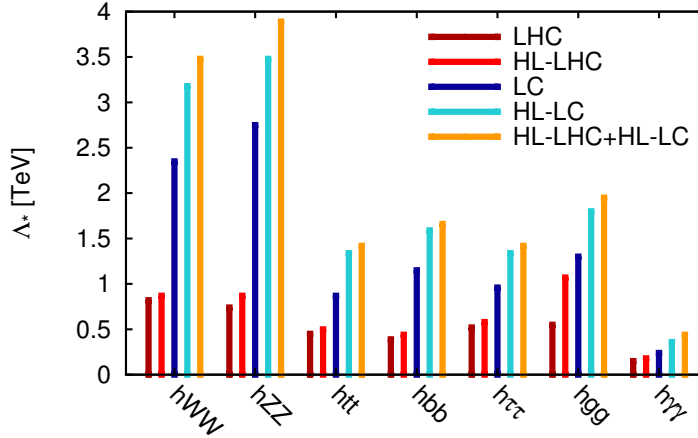


Figure 3: Effective NP scales Λ_* extracted from the Higgs coupling measurements collected in Table 1. (The ordering of the columns from left to right corresponds to the legend from up to down.) For details, see [30].

representations of $SO(5)$. As a consequence in the MCHM4 the Higgs couplings are changed universally as function of ξ , while separately for SM vector bosons and fermions in the MCHM5. The limits that can be obtained on the compositeness scale f range from below 1 TeV up to 5 TeV.

ξ	LHC	HL-LHC	LC	HL-LC	HL-LHC+HL-LC
universal	0.076	0.051	0.008	0.0052	0.0052
non-universal	0.068	0.015	0.0023	0.0019	0.0019
f [TeV]					
universal	0.89	1.09	2.82	3.41	3.41
non-universal	0.94	1.98	5.13	5.65	5.65

Table 2: Estimates of the parameter $\xi = (v/f)^2$ and the Goldstone scale f for various experimental set-ups and two different fermion embeddings (universal/MCHM4, non-universal/MCHM5); from Ref. [30].

As a last example, the interpretation of the current Higgs coupling measurements in terms of a 2-Higgs-Doublet Model (2HDM) [37] is shown. The Yukawa couplings of the two Higgs doublets are taken to be proportional to each other in flavour space. At tree-level this aligned 2HDM has five free parameters, where the mass of the charged Higgs boson, which contributes to the effective Higgs-photon coupling, is already

included. For simplicity, custodial symmetry is assumed to be fulfilled, *i.e.* the deviations of the Higgs-gauge couplings from the SM couplings are $\Delta_Z = \Delta_W \equiv \Delta_V < 0$. Figure 4 shows the comparison of the extracted free couplings according to Eq. (1) with the corresponding fit to the aligned 2HDM parameters, translated into the SM coupling deviations. The central values and the error bars agree well between these two models. The observed small deviations are due to correlations between the couplings induced in the 2HDM. If the aligned 2HDM is realized in nature, additional constraints arise from non-standard Higgs searches, from EWPTs and from flavour constraints. They are taken into account in the cyan bands. For recent work on Higgs coupling interpretations within the 2HDM with respect to wrong-sign Yukawa couplings, see *e.g.* [39].

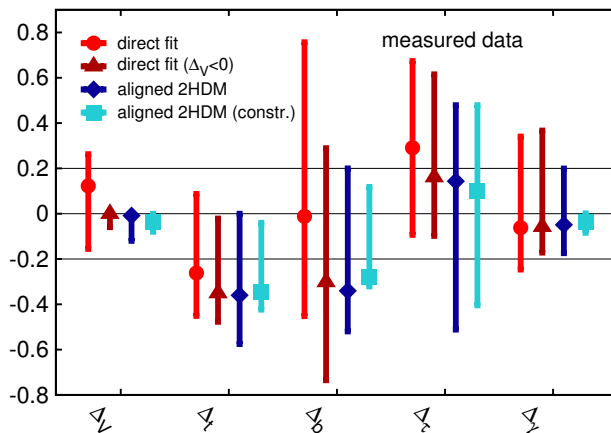


Figure 4: For the Higgs coupling measurement based on all currently available ATLAS and CMS data ($\int \mathcal{L} = 4.6 - 5(7 \text{ TeV}) + 12 - 21(8 \text{ TeV}) \text{ fb}^{-1}$): Comparison of the fits to the weak-scale couplings with a fit to the aligned 2HDM in terms of the light Higgs couplings. Figure from Ref. [38].

5 Conclusions

After the discovery of the Higgs boson it is important to reveal the true nature of the underlying dynamics of EWSB and to answer the question if it is the Higgs boson of the SM or of some NP extension. In the absence of any discovery of new particles pointing to BSM physics, the Higgs sector itself has to be explored in great detail and may turn out to be the harbinger of NP. Composite Higgs models are examples of a Higgs boson emerging from a strongly interacting sector. Although challenged by EWPTs they are still a viable option. A wide class of BSM Higgs sectors can be studied in a rather model-independent way through the effective Lagrangian approach. New physics effects are encoded in higher dimensional operators that are built from SM fields and suppressed by some high scale Λ at which NP becomes effective. Higgs coupling measurements prove useful to test such NP scales. In particular if deviations in the Higgs couplings are due to mixings of the standard Higgs with other new scalars, scales in the TeV range can be constrained by the LHC, while coupling deviations due to loop effects suffer from an additional loop suppression factor and are therefore less sensitive to Λ . Coupling fits performed within specific models, finally, complement the interpretation within the effective Lagrangian approach. With the increasing accuracy in the measurements at the next run of the LHC new exciting physics may wait for us to be discovered.

ACKNOWLEDGEMENTS

I would like to thank the organisers of LHCP14 for the invitation to give this talk, for the perfectly organised conference and for the pleasant atmosphere with a lot of inspiring discussions. I greatly acknowledge discussions with C. Grojean, S. Gupta, A. Pomarol, M. Rauch, R. Santos and M. Spira.

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